

# The Lightest Higgs Boson Mass in Pure Gravity Mediation Model

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## Abstract

We discuss the lightest Higgs boson mass in the minimal supersymmetric Standard Model with “pure gravity mediation”. By requiring that the model provides the observed dark matter density, we find that the lightest Higgs boson is predicted to be below 132 GeV. We also find that the upper limit on the lightest Higgs boson mass becomes 128 GeV, if we further assume thermal leptogenesis mechanism as the origin of baryon asymmetry of universe. The interrelations between the Higgs boson mass and the gaugino masses are also discussed.

# 1 Introduction

Supersymmetry is the most attractive candidate for beyond the Standard Model. Surprisingly, the assumption of spontaneous breaking of supersymmetry (SUSY) is enough to give rise to the masses of the superpartners of the Standard Model particles in the framework of supergravity. Scalar bosons acquire SUSY breaking soft masses at the tree level [1] and gauge fermions (gauginos) at the one-loop level [2, 3, 4]. We call this minimal setup as “pure gravity mediation”. The most attractive feature of this framework is that we do not need any additional fields for the mediation of SUSY breaking effects.

If we assume that the pure gravity mediation model is within the reach of the LHC experiments, the scale of spontaneous SUSY breaking is chosen to be around  $10^{11-12}$  GeV so that the gaugino masses generated at the one-loop level are in the hundreds GeV to the TeV range. Interestingly, the purely gravity mediated model with this mass range has many attractive features compared to the conventional models owing to the minimal setup. First of all, there is no serious Polonyi problem [5],<sup>1</sup> since there is no Polonyi field required to generate the gaugino masses. The cosmological gravitino problem [7] is also solved in this setup. This is because the gravitino mass is in the hundreds TeV range and decays before the Big-Bang Nucleosynthesis (BBN). The problems of flavor-changing neutral currents and CP violation in the supersymmetric Standard Model become very mild thanks to relatively large masses for squarks and sleptons. Furthermore, we have a good candidate of dark matter in the universe [8, 9, 10, 11]. Especially, it was pointed out in Ref. [10] that the pure gravity mediation model has a wide range of parameter space consistent with the thermal leptogenesis [12]. The unification of the gauge coupling constants at the very high energy scale also provides a strong motivation to the model.

Encouraged by these advantages, we discuss the mass of the lightest Higgs boson in the minimal SUSY Standard Model (MSSM). We find the upper limits on the lightest Higgs boson mass is predicted to be about 132 GeV. The requirement of the successful leptogenesis lowers the upper limit down to about 128 GeV. These predictions will be tested soon at the LHC experiments.

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<sup>1</sup>See also Ref. [6] for the Polonyi problem in dynamical supersymmetry breaking models.

The organization of the paper is as follows. In section 2 and 3, we discuss the masses of the MSSM superparticles and the lightest Higgs boson in the pure gravity mediation model. In section 4, we derive the upper limits on the lightest Higgs boson mass by requiring the consistent dark matter density. We also discuss the consistency of the model with thermal leptogenesis. In section 5, we discuss the interrelation between the lightest Higgs boson mass and the gaugino masses. The final section is devoted to our conclusions.

## 2 Purely Gravity Mediated SUSY Breaking

### Sfermions and Gauginos

In the pure gravity mediation model, the only new ingredient other than the MSSM fields is a (dynamical) SUSY breaking sector. Then, the soft SUSY breaking masses of squarks, sleptons and Higgs bosons are mediated by the supergravity effects at the tree-level. With a generic Kähler potential, all the scalar bosons obtain the SUSY breaking masses of the order of the gravitino mass,  $m_{3/2}$ . For the gaugino masses, on the other hand, tree-level contributions in the supergravity are extremely suppressed since we have no SUSY breaking fields which are singlet under any symmetries.

At the one-loop level, however, the gaugino masses are generated by the supergravity effects without having singlet SUSY breaking fields [2, 3, 4]. The one-loop generated so-called anomaly-mediated gaugino masses are given by

$$M_a = -\frac{b_a g_a^2}{16\pi^2} m_{3/2} , \quad (1)$$

where  $a$  denotes the three standard-model gauge groups ( $a = 1, 2, 3$ ),  $g_a$  gauge coupling constants, and  $b_a$  coefficients of the renormalization-group equations of  $g_a$ , i.e.  $b_a = (-33/5, -1, 3)$ . Therefore, the framework of the pure gravity mediation does not require any new mediator fields to make the superparticles massive.

The important feature of the anomaly-mediated gaugino spectrum is that the lightest gaugino is the neutral wino. The charged wino is slightly heavier than the neutral one by about 155 MeV–170 MeV due to one-loop gauge boson contributions [13]. Thus, it is

quite tempting to explore whether the neutral wino can be a candidate for dark matter. In fact, thermal relic density of the wino is consistent with the observed dark matter density for  $M_2 \simeq 2.7 \text{ TeV}$  [14, 15]. The relatively large mass of thermal wino dark matter stems from the large annihilation cross section of the winos into  $W$ -bosons. The lighter wino than  $2.7 \text{ TeV}$  is also a good candidate once the relic abundance is provided by the non-thermal production by the late time decay of the gravitinos which were produced when the universe had high temperature [8, 9, 10, 11]. As we will discuss, the consistent mass range of the wino dark matter puts upper limit on the lightest Higgs boson mass in the pure gravity mediation model.

## Higgs Sector

In the purely gravity mediated models, we also expect that the two additional mass parameters in the Higgs sector, the so-called  $\mu$ - and  $B$ -parameters, are also of the order of the gravitino mass. Indeed, without any special symmetries, we expect the following Kähler potential,

$$K \ni c H_u H_d + \frac{c'}{M_{PL}^2} Z^\dagger Z H_u H_d + h.c.. \quad (2)$$

Here,  $Z$  is a chiral superfield in the hidden sector, which may or may not be a composite field,  $M_{PL}$  is the reduced Planck scale, and  $c$  and  $c'$  are coefficients of  $O(1)$ .<sup>2</sup> The above Kähler potential leads to the  $\mu$ - and the  $B$ -parameters [16]

$$\mu_H = c m_{3/2}, \quad (3)$$

$$B\mu_H = c m_{3/2}^2 + c' \frac{|F_X|^2}{M_{PL}^2}, \quad (4)$$

where  $F_Z$  is the vacuum expectation value of the  $F$ -component of  $Z$ .<sup>3</sup> Thus,  $\mu$ - and  $B$ -parameters are both expected to be of  $O(m_{3/2})$ , and hence, the higgsinos are expected to be as heavy as the sfermions and the gravitino.

For successful electroweak symmetry breaking, one linear combination of the Higgs bosons should be light which is denoted by  $h = \sin \beta H_u - \cos \beta H_d^*$  with a mixing angle

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<sup>2</sup>Even if  $Z$  is a composite field,  $c'$  can be  $O(1)$ .

<sup>3</sup>We assume that the vacuum expectation value of  $Z$  is much smaller than  $M_{PL}$ .

$\beta$ . Here,  $H_u$  and  $H_d$  are up- and down-type Higgs bosons, respectively. In terms of the mass parameters, the mixing angle is given by

$$\sin 2\beta = \frac{2B\mu_H}{m_{H_u}^2 + m_{H_d}^2 + 2|\mu_H|^2} , \quad (5)$$

while the light Higgs boson requires a tuning between mass parameters,

$$(|\mu_H|^2 + m_{H_u}^2)(|\mu_H|^2 + m_{H_d}^2) - (B\mu_H)^2 \simeq 0 , \quad (6)$$

at the energy scale of the heavy scalars. Therefore, by remembering that squared masses of  $H_u$  and  $H_d$ ,  $m_{H_{u,d}}^2$ , as well as  $B$  and  $\mu_H$  are of the order of the gravitino mass, the mixing angle  $\beta$  is expected to be of  $\mathcal{O}(1)$ .<sup>4</sup>

In summary of the pure gravity mediation, the mass spectrum and the Higgs mixing angle are expected to be;

- The sfermions and the gravitino are in the  $\mathcal{O}(10^{4-6})$  GeV range.
- The higgsinos and the heavier Higgs bosons are in the  $\mathcal{O}(10^{4-6})$  GeV range.
- The gauginos are in the hundreds to thousands TeV range.
- The Higgs mixing angle is of order of unity, i.e.  $\tan \beta = \mathcal{O}(1)$ .

Notice that the pure gravity mediation model has some similarities to the Split Supersymmetry [17, 18, 19] for  $M_{\text{SUSY}} \simeq 10^{4-6}$  GeV. The important difference is that we do not expect  $M_{\text{SUSY}} \gg 10^{4-6}$  GeV, since we rely on the anomaly-mediated gaugino masses in the pure gravity mediation model.<sup>5</sup> In this sense, the pure gravity mediation model is more close to the PeV-scale Supersymmetry [21] and the Spread Supersymmetry [22]. The other important and more practical difference is the size of  $\mu$ -term. In the Split Supersymmetry, it is assumed that the higgsinos are also in the TeV range, while we consider they are as heavy as the gravitino. Therefore, we can distinguish our scenario from the Split Supersymmetry by searching for the higgsinos at the collider experiments.

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<sup>4</sup>Hereafter, we treat the  $\mu_H$  and  $B$  parameters as real valued parameters just for simplicity, although our discussions are not changed even if they are complex valued.

<sup>5</sup>See discussions on the possible cancellation of the anomaly-mediated gaugino masses [19, 20].

### 3 The Lightest Higgs Boson Mass

Below the scale of the heavy scalars,  $M_{\text{SUSY}} = \mathcal{O}(m_{3/2})$ , the Higgs sector consists of the light Higgs boson  $h$  whose potential is given by,

$$V(h) = \frac{\lambda}{2}(h^\dagger h - v^2)^2, \quad (7)$$

where  $v \simeq 174.1 \text{ GeV}$  is determined to reproduce the observed  $Z$  boson mass. At the tree-level, the Higgs coupling constant  $\lambda$  satisfies the so-called the SUSY relation,

$$\lambda = \frac{1}{4} \left( \frac{3}{5} g_1^2 + g_2^2 \right) \cos^2 2\beta. \quad (8)$$

This is the famous and remarkable feature of the MSSM where the physical Higgs boson mass,  $m_h^2 = 2\lambda v^2$ , is not a free parameter but a prediction of the model.

Below  $M_{\text{SUSY}}$ , the above SUSY relation is violated by the SUSY breaking effects through the radiative corrections [23]. The first contribution to deviates the SUSY relation is the radiative correction through the renormalization-group equation. At the one-loop level, the renormalization-group equation is roughly given by

$$\frac{d\lambda}{dt} \sim \frac{12}{16\pi^2} (\lambda^2 + \lambda y_t^2 - y_t^4), \quad (9)$$

where  $y_t$  denotes the top Yukawa coupling, and we have neglected gaugino couplings for illustrative purpose. By imposing the SUSY relation in Eq. (8) at the renormalization scale  $Q = M_{\text{SUSY}}$ , the renormalization-group equation can be approximately solved by,

$$\lambda(m_h) \sim \lambda(M_{\text{SUSY}}) + \frac{12}{(4\pi)^2} y_t^4 \ln \frac{M_{\text{SUSY}}}{m_h}. \quad (10)$$

Therefore, we expect that the physical Higgs mass receives a large positive correction for  $M_{\text{SUSY}} = \mathcal{O}(10^{4-6}) \text{ GeV}$ .

The second contribution which deviates the SUSY relation comes from the finite correction to the Higgs quartic coupling from the trilinear couplings. At the one-loop level, this contribution is given by,

$$\delta\lambda \simeq \frac{6}{(4\pi)^2} y_t^4 \left( \frac{X_t^2}{m_t^2} - \frac{1}{12} \frac{X_t^4}{m_t^4} \right),$$

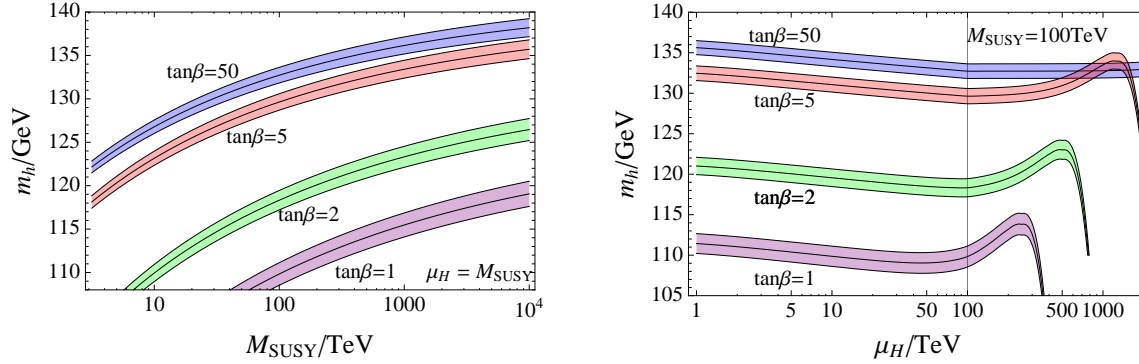


Figure 1: Left) The lightest Higgs boson mass as a function of  $M_{\text{SUSY}}$  with  $\mu_H = M_{\text{SUSY}}$ . The result is slightly lighter than the one in Ref. [25] due to the large  $\mu$ -term (see the right panel). Right) The lightest Higgs boson mass as a function of  $\mu_H$  for  $M_{\text{SUSY}} = 100 \text{ TeV}$ . In both panels, the color bands show the  $1\sigma$  error of the top quark mass,  $m_{\text{top}} = 173.2 \pm 0.9 \text{ GeV}$  [26], while we have taken the central value of the strong coupling constant,  $\alpha(M_Z) = 0.1184 \pm 0.0007$  [27]. We have also fixed the gaugino masses to  $M_1 = 900 \text{ GeV}$ ,  $M_2 = 300 \text{ GeV}$  and  $M_3 = -2500 \text{ GeV}$  as reference values, although the predicted Higgs boson mass is insensitive to the gaugino masses.

$$\begin{aligned}
X_t &= A_t - \mu_H \cot \beta \simeq -\mu_H \cot \beta, \\
m_t^2 &= m_{t_L}^2 + m_{t_R}^2,
\end{aligned} \tag{11}$$

where  $A_t$  is the trilinear coupling constant between Higgs and stops, and  $m_{t_{L,R}}^2$  denote the squared soft masses of the left and right stops. Notice that  $A_t$  is expected to be suppressed at the tree-level of the supergravity.<sup>6</sup> Since  $\mu_H$  is in the gravitino mass range and  $\tan \beta = O(1)$ , this correction can be sizable in the pure gauge mediation model.

With these discussions in mind, we compute the lightest Higgs boson mass for given  $M_{\text{susy}}$ ,  $\mu_H$  and  $\tan \beta$ . In our analysis, we numerically solve the full one-loop renormalization-group equations of the Higgs quartic coupling, the gauge couplings, the gaugino couplings, the Yukawa couplings of the third generation fermions, and the gaugino masses given in Ref. [18]. We also include the weak scale threshold corrections to those parameters in accordance with Ref. [24, 25]. Notice that we decouple the higgsino contributions to the renormalization group equations at  $Q = \mu_H$  and match the coupling constants below and above that scale, since  $\mu_H$  is much heavier than the TeV scale.

In Fig. 1, we show the parameter dependancies of the lightest Higgs boson mass. The

<sup>6</sup>Here, we again assume that  $\langle Z \rangle \ll M_{\text{PL}}$ .

left panel of the figure shows the Higgs boson mass as a function of  $M_{\text{SUSY}}$ . In the figure, we have taken  $\mu_H = M_{\text{SUSY}}$ . The color bands represent the  $1\sigma$  error on the top quark mass,  $m_{\text{top}} = 173.2 \pm 0.9 \text{ GeV}$ .<sup>7</sup> The figure shows that the lightest Higgs boson mass can easily exceed the lower bound from the LEP experiments,  $m_h > 114.4 \text{ GeV}$  [28] for  $\tan\beta = O(1)$ . The lightest Higgs boson mass larger than  $120 \text{ GeV}$  is also easily realized for the wide range of parameters.

The right panel shows the  $\mu_H$  dependence of the lightest Higgs boson mass for  $M_{\text{SUSY}} = 100 \text{ TeV}$ . The color bands again correspond to the  $1\sigma$  error of the top quark mass. The figure shows that the lightest Higgs boson mass decreases monotonically for the larger  $\mu_H$  for relatively small  $\mu_H$  region, i.e.  $\mu_H \ll M_{\text{SUSY}}$ . This is due to the fact that the gaugino coupling contributions increase the Higgs quartic coupling constant at the low energy via the renormalization group equations. For  $\mu_H = \mathcal{O}(M_{\text{SUSY}})$ , on the other hand, the finite threshold correction to the Higgs quartic coupling in Eq. (11) becomes important especially for the small  $\tan\beta$ . The peaks of the lightest Higgs boson mass correspond to the parameters which satisfy  $X_t \simeq \sqrt{6}m_{\tilde{t}}$ .

In Fig. 2, we show the contour plot of the lightest Higgs boson mass as a function of  $M_{\text{SUSY}}$  and  $\tan\beta$ . In the figure, we have used the central values of the  $1\sigma$  errors of the strong coupling constant and the top quark masses. For given parameters, we have used the gaugino masses which are obtained by solving the full one-loop renormalization group equations with the anomaly-mediated boundary condition in Eq.(1) at  $Q = M_{\text{SUSY}}$  with  $m_{3/2} = M_{\text{SUSY}}$ . The color bands represent the effects of the theoretical uncertainty of the ratio  $\mu_H/M_{\text{SUSY}}$  on the lightest Higgs boson mass. We have taken  $M_{\text{SUSY}}/3 < \mu_H < 3M_{\text{SUSY}}$ . The figure shows that the effect of the theoretical uncertainty is sizable for a small  $\tan\beta$  region where the finite correction in Eq. (11) to the Higgs quartic coupling can be large.



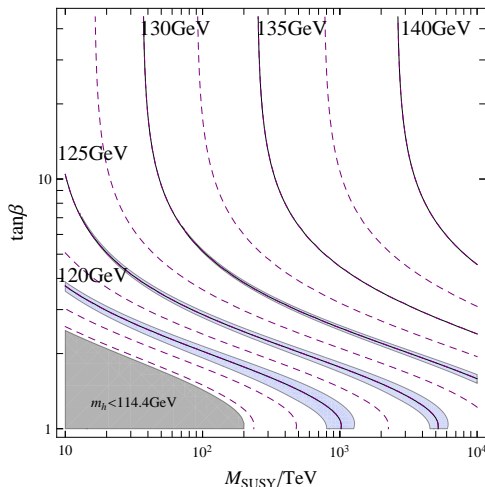


Figure 2: The contour plot of the lightest Higgs boson mass. The bands for  $m_h = 120, 125, 130, 135, 140$  GeV represent the effects of the theoretical uncertainty of the ratio  $\mu_H/M_{\text{SUSY}}$  to the lightest Higgs boson mass. We have assumed that  $M_{\text{SUSY}}/3 < \mu_H < 3M_{\text{SUSY}}$ . We have used the central values of the  $1\sigma$  errors of the strong coupling constant and the top quark mass.

## 4 Upper Bound on The Lightest Higgs Boson Mass

As we mentioned above, the lightest superparticle in the pure gravity mediation is the neutral wino which can be a good dark matter candidate. The important feature of the wino dark matter scenario is that the current abundance consists of two contributions. The one is from the thermal relic density of the wino itself, and the other from the late time decay of the gravitino. Notice that the late time decay of the gravitino does not cause the gravitino problems since the gravitino decay before the BBN [7].

The thermal relic density of the wino is determined by the annihilation cross section of the winos into the  $W$ -bosons via the weak interaction. The resultant relic density  $\Omega^{(TH)}h^2(M_2)$  can be found in Ref. [14, 15]. The thermal relic density saturates the observed dark matter density  $\Omega h^2 \simeq 0.11$  for  $M_2 \simeq 2.7$  TeV, while it is quickly decreasing for the lighter wino. The non-thermal relic density is, on the other hand, proportional to

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<sup>7</sup>We have not shown the uncertainty due to the  $1\sigma$  error on the strong coupling constant which is smaller than the one from the top mass error.

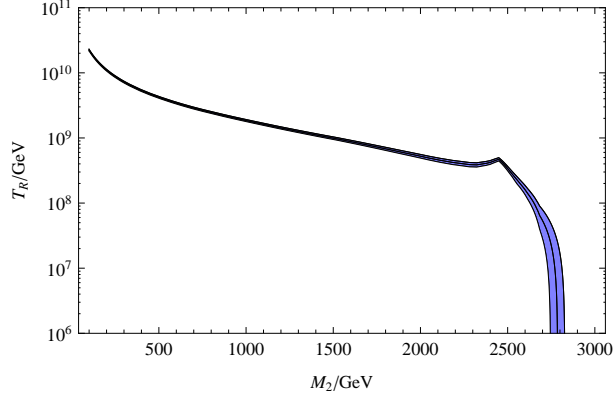


Figure 3: *The required reheating temperature of universe as a function of the wino mass for the consistent dark matter density. We have used the thermal relic density given in Refs. [14, 15]. The color bands correspond to the  $1\sigma$  error of the observed dark matter density,  $\Omega h^2 = 0.1126 \pm 0.0036$  [29]. For a detailed discussion see also Ref. [10].*

the gravitino number density which is proportional to the reheating temperature  $T_R$  after inflation,

$$\Omega^{(NT)} h^2(M_2, T_R) \simeq 0.16 \times \left( \frac{M_2}{300 \text{ GeV}} \right) \left( \frac{T_R}{10^{10} \text{ GeV}} \right) . \quad (12)$$

The total relic density is given by,

$$\Omega h^2 = \Omega^{(TH)}(M_2) + \Omega^{(NT)} h^2(M_2, T_R) . \quad (13)$$

Therefore, the wino which is lighter than 2.7 TeV can be the dominant component of the dark matter for an appropriate reheating temperature.

Fig. 3 shows the required reheating temperature of universe as a function of the wino mass for the consistent dark matter density. The color bands correspond to the  $1\sigma$  error of the observed dark matter density,  $\Omega h^2 = 0.1126 \pm 0.0036$  [29]. It is remarkable that the required reheating temperature is consistent with the lower bound on  $T_R$  for the successful thermal leptogenesis,  $T_R \gtrsim 10^{9.5} \text{ GeV}$  [12].

Now, let us interrelate the wino dark matter density and the lightest Higgs boson mass. As we have discussed, the lightest Higgs boson mass is determined for given  $M_{\text{SUSY}} = \mathcal{O}(m_{3/2})$  and  $\tan \beta$ . The wino mass is, on the other hand, is given by,

$$M_2 \simeq 3 \times 10^{-3} m_{3/2} , \quad (14)$$

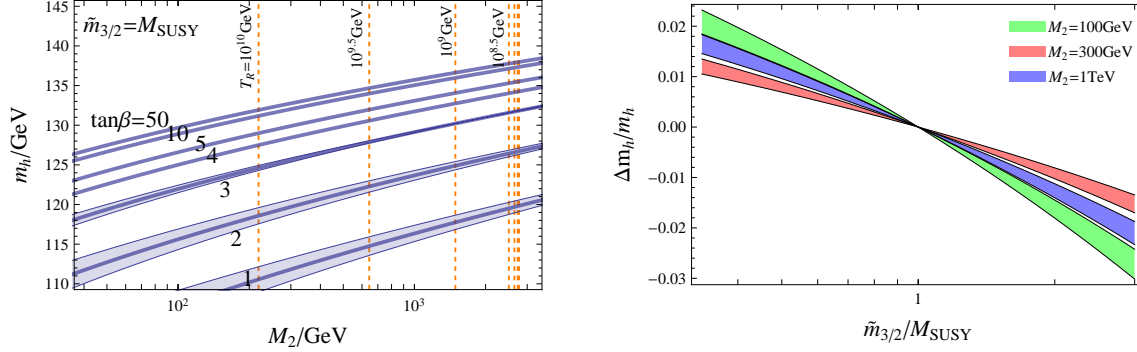


Figure 4: Left) The lightest Higgs boson mass for a given wino mass. We also show the required reheating temperature for the successful wino dark matter scenario as dashed lines (see Fig. 3). Right) The lightest Higgs boson mass dependence on the theoretical uncertainty from the ratio  $\tilde{m}_{3/2}/M_{\text{SUSY}}$ .

with the anomaly-mediated boundary condition in Eq. (1) at  $Q = M_{\text{SUSY}}$ .<sup>8</sup> Thus, with the theoretical uncertainty of the ratio  $m_{3/2}/M_{\text{SUSY}}$ , we can interrelate the Higgs boson mass and the wino mass.

In Fig. 4, we show the lightest Higgs boson mass as a function of the wino mass for  $\tilde{m}_{3/2} = M_{\text{SUSY}}$ . (Here, we have used  $\tilde{m}_{3/2} \simeq m_{3/2}$  instead of  $m_{3/2}$ . The definition of  $\tilde{m}_{3/2}$  is given in Eq. (20).) The color bands of the left panel again the effects of the theoretical uncertainty of the ratio  $\mu_H/M_{\text{SUSY}}$  as discussed in the previous section. In the figure, we also show the contour plot of the required reheating temperature for the wino dark matter scenario. The figure shows that the Higgs boson mass is predicted to be lighter for the higher reheating temperature for a given  $\tan\beta$ .

The right panel of the figure shows the dependence of the lightest Higgs boson mass on the theoretical uncertainty of the ratio,  $\tilde{m}_{3/2}/M_{\text{SUSY}}$ . The each color band corresponds to  $3 < \tan\beta < 50$  for a given value of  $M_2$ . The smaller  $\tan\beta$  is, the larger the effect of the uncertainty is. The figure shows that the effect of the theoretical uncertainty from the ratio  $\tilde{m}_{3/2}/M_{\text{SUSY}}$  is less than about 2% for the wide range of parameters.

From the Fig. 4, we can derive the upper limit on the reheating temperature after

<sup>8</sup> The current experimental bound on  $M_2$  is  $M_2 \geq 88 \text{ GeV}$  obtained at the LEP experiments [30]. The mass of the wino dark matter is also constrained to  $M_2 \gtrsim 200 - 250 \text{ GeV}$  by the observed light element abundance through the dark matter annihilation at the BBN era [31].

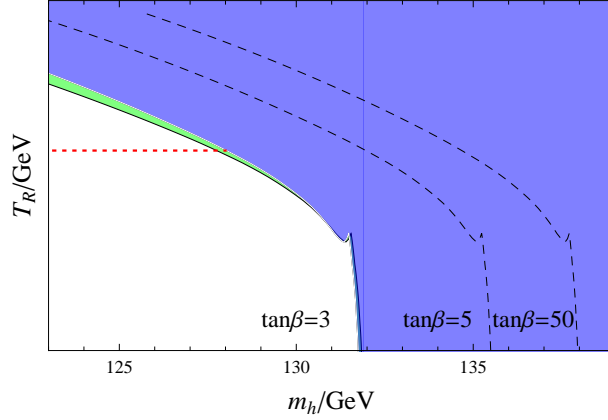


Figure 5: The upper limit on the reheating temperature as a function of the lightest Higgs boson mass. The green band represents the effects of the theoretically uncertain ratio  $\mu_H/M_{\text{SUSY}}$  which we have taken between  $M_{\text{SUSY}}/3 < \mu_H < 3M_{\text{SUSY}}$ . The effect of the theoretical uncertainty from the ratio  $\tilde{m}_{3/2}/M_{\text{SUSY}}$  can be read off from the right panel of Fig. 4.

inflation for a given lightest Higgs boson mass. In Fig. 5, we show the upper limit on  $T_R$  for  $\tan \beta = 3$  which is the typical value expected in the pure gravity mediation. The thin green band represents the effects of the theoretical uncertainty from the  $\mu_H/M_{\text{SUSY}}$  where we have again taken  $M_{\text{SUSY}}/3 < \mu_H < 3M_{\text{SUSY}}$ . We also show the upper limit on the results for  $\tan \beta = 5$  and  $\tan \beta = 50$  for comparison, although  $\tan \beta = 50$  is quite unlikely in the pure gravity mediation.

The figure shows that the dark matter constraint puts the upper limit on the Higgs boson mass is about  $m_h \simeq 132$  GeV. Furthermore, the requirement of thermal leptogenesis puts more stringent constraint on the Higgs boson mass down to  $m_h = 128$  GeV. These upper limits will be tested at the LHC experiments very soon. The effects of the theoretical uncertainties and the  $1\sigma$  error on the top quark mass which are not included in this figure can be read off from the previous figures.

Before closing this section, let us comment on the threshold corrections to the gaugino

masses at the higgsino threshold [2, 8],

$$\Delta M_1^{(higgsino)} = \frac{3}{5} \frac{g_1^2}{16\pi^2} L, \quad (15)$$

$$\Delta M_2^{(higgsino)} = \frac{g_2^2}{16\pi^2} L, \quad (16)$$

$$\Delta M_3^{(higgsino)} = 0, \quad (17)$$

where

$$L \equiv \mu_H \sin 2\beta \frac{m_A^2}{|\mu_H|^2 - m_A^2} \ln \frac{|\mu_H|^2}{m_A^2}. \quad (18)$$

Here,  $m_A$  is the mass of heavy Higgs bosons which is given by

$$m_A^2 = m_{H_u}^2 + m_{H_d}^2 + 2|\mu_H|^2. \quad (19)$$

For  $\mu_H = \mathcal{O}(m_{3/2})$ ,  $\Delta M_a^{(Higgs)}$  (for  $a = 1, 2$ ) can be comparable to the anomaly-mediated gaugino masses. In the above analysis, we have introduced an effective gravitino mass scale,

$$\tilde{m}_{3/2} = m_{3/2} + L, \quad (20)$$

so that  $M_2$  is expressed by,

$$M_2 = \frac{g_2^2}{16\pi^2} (m_{3/2} + L) = \frac{g_2^2}{16\pi^2} \tilde{m}_{3/2}. \quad (21)$$

The numerical value of the wino mass for a given  $\tilde{m}_{3/2}$  is obtained by replacing  $m_{3/2}$  to  $\tilde{m}_{3/2}$  in Eq. (14). Since either  $m_{3/2}$  or  $\tilde{m}_{3/2}$  is expected to be in the same order of  $M_{\text{SUSY}}$ ,<sup>9</sup> we estimated the effects of the theoretical uncertainties by sweeping  $M_{\text{SUSY}}/3 < \tilde{m}_{3/2} < 3M_{\text{SUSY}}$ .

## 5 Gaugino mass and Higgs boson mass

Finally, let us briefly discuss the interrelation between the lightest Higgs boson mass and the gaugino masses. In the pure gravity mediation, the gauginos are the only superparticles which can be discovered at the LHC experiments, since the sfermions are expected

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<sup>9</sup>If there is a cancellation between  $m_{3/2}$  and  $L$ , the effective gravitino mass  $\tilde{m}_{3/2}$  can be very small compared with  $M_{\text{SUSY}}$ , which leads to a very large lightest Higgs boson mass for a given wino mass. We do not consider such cancellation in this paper.

to be as heavy as  $\mathcal{O}(10^{4-6})$  GeV.<sup>10</sup> Even worse, the gluino pole mass obtained by the anomaly-mediated boundary condition at  $Q = M_{\text{SUSY}}$  is about 7 – 10 times larger than the wino mass. For example, the gluino mass is about 4 TeV for  $M_2 = 500$  GeV. This feature implies that the search of the superparticles at the LHC experiments is very difficult in most parameter space of the pure gravity mediation.

One possible way out from this pessimistic prediction can be obtained from the higgsino contributions to the gaugino masses in Eqs. (15)-(17). That is, for a given value of  $M_2$ , the gluino mass is now given by,

$$\begin{aligned} M_3 &\simeq -(7-10) \times \frac{M_2}{1+\delta_{\tilde{H}}}, \\ \delta_{\tilde{H}} &= \sin 2\beta \frac{\mu_H}{m_{3/2}} \frac{m_A^2}{|\mu_H|^2 - m_A^2} \ln \frac{|\mu_H|^2}{m_A^2} = \mathcal{O}(1) \times \sin^2 2\beta. \end{aligned} \quad (22)$$

In the final expression of  $\delta_{\tilde{H}}$ , we have used Eq. (5). Therefore, the gluino mass can be significantly smaller than the above mentioned value for  $\tan \beta = \mathcal{O}(1)$ .<sup>11</sup>

In Fig. 6, we show the contour plot of the lightest possible gluino mass for given wino and Higgs boson masses with the higgsino threshold effects on the wino mass. Here, we are assuming  $\delta_{\tilde{H}} = 3 \sin^2 2\beta$ . The dotted contours show the gluino mass with the anomaly-mediated boundary conditions ( $\delta_{\tilde{H}} = 0$ ) for comparison. The dotted contours are insensitive to the Higgs boson mass. The figure shows that the gluino can be significantly lighter the prediction with the anomaly-mediated boundary condition for a small  $\tan \beta$ , while the effect is vanishing for  $\tan \beta = \mathcal{O}(10)$ .

It should be also noted that we can put the lower limit on the lightest possible gluino mass for a given wino mass once the Higgs mass is determined experimentally. For example, the figure shows that the gluino can be as light as 1.5 TeV for  $m_h \simeq 125$  GeV and  $M_2 \simeq 400$  GeV. These features of the pure gravity mediation enhance the testability of the model at the LHC experiments.

<sup>10</sup>See for example Ref. [32, 33, 34, 35] for the search of the gauginos at the LHC experiments.

<sup>11</sup>Depending on the sign (or the complex phase) of  $\delta_{\tilde{H}}$ , the gluino can be significantly heavier than the prediction with the anomaly-mediation boundary condition.

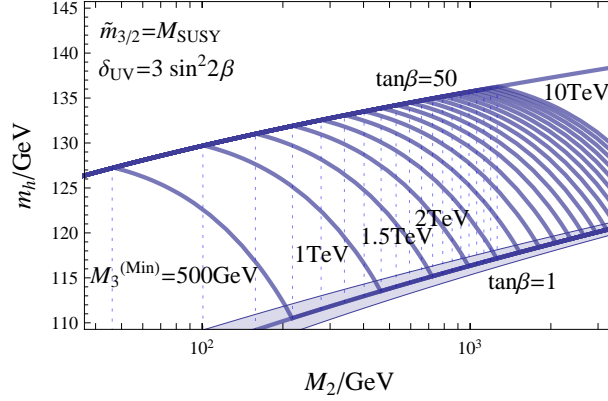


Figure 6: The contours of the lightest possible gluino mass as a function of the wino and the lightest Higgs boson masses. We have assumed that  $\delta_{\tilde{H}} = 3 \sin^2 2\beta$ . The dashed contours show the gluino mass prediction without the higgsino threshold effects. The effects of the theoretical uncertainties from the ratios  $\mu_H/M_{SUSY}$  and  $\tilde{m}_{3/2}/M_{SUSY}$  can be read from the previous figures.

## 6 Conclusions

In this paper, we discussed the lightest Higgs boson mass in the pure gravity mediation model which consistently provides the observed dark matter density. The important features of the pure gravity mediation model are (i) the sfermions, the higgsinos and the gravitinos are as heavy as  $10^{4-6}$  GeV (ii) the gaugino masses are in the TeV range and deviating from the so called GUT relation (iii)  $\tan \beta = \mathcal{O}(1)$ . With these features, we found the upper limit on the lightest Higgs boson mass is predicted to be about 132 GeV. The requirement of the successful leptogenesis lowers the upper limit down to about 128 GeV. These predictions will be tested at the LHC experiments very soon.

We also discussed the interrelation between the lightest Higgs boson mass and the gaugino masses. We found that the gluino mass for given wino and Higgs boson masses can be significantly smaller than the predictions with the anomaly-mediated boundary conditions due to the higgsino threshold effects on the wino mass. Therefore, the pure gravity mediation model can be extensively tested by the interplay between the Higgs searches and the gaugino searches at the LHC experiments.

In our discussion, we have not studied the constraints on the wino dark matter scenario

from the cosmic ray experiments. Since the wino has a rather large annihilation cross section into  $W$ -boson, it is promising that the model can be tested through the cosmic ray observations. The detailed analysis is in preparation.<sup>12</sup>

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## References

- [1] For a review, H. P. Nilles, Phys. Rept. **110** (1984) 1.
- [2] G. F. Giudice, M. A. Luty, H. Murayama and R. Rattazzi, JHEP **9812**, 027 (1998).
- [3] L. Randall and R. Sundrum, Nucl. Phys. B **557**, 79 (1999).
- [4] M. Dine and D. MacIntire, Phys. Rev. D **46**, 2594 (1992) [hep-ph/9205227].
- [5] G. D. Coughlan, W. Fischler, E. W. Kolb, S. Raby and G. G. Ross, Phys. Lett. B **131**, 59 (1983).
- [6] M. Ibe, Y. Shinbara and T. T. Yanagida, Phys. Lett. B **639**, 534 (2006) [hep-ph/0605252].
- [7] M. Kawasaki, K. Kohri and T. Moroi, Phys. Rev. D **71** (2005) 083502 [arXiv:astro-ph/0408426]; K. Jedamzik, Phys. Rev. D **74**, 103509 (2006) [arXiv:hep-ph/0604251], and references therein.
- [8] T. Gherghetta, G. F. Giudice and J. D. Wells, Nucl. Phys. B **559**, 27 (1999) [arXiv:hep-ph/9904378].
- [9] T. Moroi and L. Randall, Nucl. Phys. B **570**, 455 (2000) [hep-ph/9906527].

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<sup>12</sup>See for example Ref.[36], for earlier works.



- [10] M. Ibe, R. Kitano, H. Murayama and T. Yanagida, Phys. Rev. D **70**, 075012 (2004) [arXiv:hep-ph/0403198]; M. Ibe, R. Kitano and H. Murayama, Phys. Rev. D **71**, 075003 (2005) [arXiv:hep-ph/0412200].
- [11] N. Arkani-Hamed, A. Delgado and G. F. Giudice, Nucl. Phys. B **741**, 108 (2006) [hep-ph/0601041].
- [12] M. Fukugita and T. Yanagida, Phys. Lett. **B174** (1986) 45; For reviews, W. Buchmuller, R. D. Peccei and T. Yanagida, Ann. Rev. Nucl. Part. Sci. **55**, 311 (2005) [arXiv:hep-ph/0502169]; S. Davidson, E. Nardi and Y. Nir, Phys. Rept. **466**, 105 (2008) [arXiv:0802.2962 [hep-ph]].
- [13] J. L. Feng, T. Moroi, L. Randall, M. Strassler and S. f. Su, Phys. Rev. Lett. **83**, 1731 (1999).
- [14] J. Hisano, S. Matsumoto, M. Nagai, O. Saito and M. Senami, Phys. Lett. B **646**, 34 (2007) [hep-ph/0610249].
- [15] M. Cirelli, A. Strumia and M. Tamburini, Nucl. Phys. B **787**, 152 (2007) [arXiv:0706.4071 [hep-ph]].
- [16] K. Inoue, M. Kawasaki, M. Yamaguchi and T. Yanagida, Phys. Rev. D **45**, 328 (1992).
- [17] N. Arkani-Hamed and S. Dimopoulos, JHEP **0506**, 073 (2005) [hep-th/0405159].
- [18] G. F. Giudice and A. Romanino, Nucl. Phys. B **699**, 65 (2004) [Erratum-ibid. B **706**, 65 (2005)] [hep-ph/0406088].
- [19] N. Arkani-Hamed, S. Dimopoulos, G. F. Giudice and A. Romanino, Nucl. Phys. B **709**, 3 (2005) [hep-ph/0409232].
- [20] K. -I. Izawa, T. Kugo and T. T. Yanagida, Prog. Theor. Phys. **125**, 261 (2011) [arXiv:1008.4641 [hep-ph]].
- [21] J. D. Wells, Phys. Rev. D **71**, 015013 (2005) [hep-ph/0411041].
- [22] L. J. Hall and Y. Nomura, arXiv:1111.4519 [hep-ph].
- [23] Y. Okada, M. Yamaguchi and T. Yanagida, Phys. Lett. B **262**, 54 (1991).

- [24] N. Bernal, A. Djouadi and P. Slavich, JHEP **0707**, 016 (2007) [arXiv:0705.1496 [hep-ph]].
- [25] G. F. Giudice and A. Strumia, arXiv:1108.6077 [hep-ph].
- [26] M. Lancaster [Tevatron Electroweak Working Group and for the CDF and D0 Collaborations], arXiv:1107.5255 [hep-ex].
- [27] S. Bethke, Eur. Phys. J. C **64**, 689 (2009) [arXiv:0908.1135 [hep-ph]].
- [28] R. Barate *et al.* [LEP Working Group for Higgs boson searches and ALEPH and DELPHI and L3 and OPAL Collaborations], Phys. Lett. B **565**, 61 (2003) [hep-ex/0306033].
- [29] E. Komatsu *et al.* [WMAP Collaboration], Astrophys. J. Suppl. **192**, 18 (2011) [arXiv:1001.4538 [astro-ph.CO]].
- [30] A. Heister *et al.* [ALEPH Collaboration], Phys. Lett. B **533**, 223 (2002) [hep-ex/0203020].
- [31] J. Hisano, M. Kawasaki, K. Kohri and K. Nakayama, Phys. Rev. D **79**, 063514 (2009) [Erratum-ibid. D **80**, 029907 (2009)] [arXiv:0810.1892 [hep-ph]].
- [32] M. Ibe, T. Moroi and T. T. Yanagida, Phys. Lett. B **644**, 355 (2007) [hep-ph/0610277].
- [33] S. Asai, T. Moroi, K. Nishihara and T. T. Yanagida, Phys. Lett. B **653**, 81 (2007) [arXiv:0705.3086 [hep-ph]].
- [34] S. Asai, T. Moroi and T. T. Yanagida, Phys. Lett. B **664**, 185 (2008) [arXiv:0802.3725 [hep-ph]].
- [35] D. S. M. Alves, E. Izaguirre and J. G. Wacker, arXiv:1108.3390 [hep-ph].
- [36] M. Fujii and K. Hamaguchi, Phys. Rev. D **66**, 083501 (2002) [hep-ph/0205044];  
M. Fujii and M. Ibe, Phys. Rev. D **69**, 035006 (2004) [hep-ph/0308118].